IMPROVEMENT OF BEAM INTENSITIES FOR ION BEAMS WITH CHARGE-TO-MASS RATIO OF 1/3 WITH THE TWO-FREQUENCY HEATING TECHNIQUE

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Abstract

In order to increase the beam intensities of ions with a charge-to-mass ratio of about 1/3 like Ar^{13+} and Fe^{18+} from an electron cyclotron resonance ion source (ECRIS), a technique was tested to feed multiple microwaves with different frequencies, the so-called two-frequency heating technique. Our group studied the improvements when the two frequencies are close together each with a power of more than 1kW using an 18GHz ECRIS installed in the Heavy Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS). The intensities of highly charged ions of C, Ar, Fe and Ni were increased successfully.

INTRODUCTION

Although the best ion species for heavy ion radiotherapy principally depends on the type and location of a tumor, a carbon ion beam was finally chosen at the Heavy Ion Medical Accelerator in Chiba (HIMAC) due to its better biological dose distributions than helium or neon for the typical depth and thickness of a tumor. Presently, seven carbon-ion radiotherapy dedicated facilities are operated worldwide. Four of the seven facilities are located in Japan. For the production of the carbon ions, ECRISs have been developed and utilized because its lifetime is longer than other types of ion sources. The ion sources satisfy medical requirements at each facility[1].

The Gunma University Heavy-ion Medical Centre (GHMC)[2], the Saga Heavy Ion Medical Accelerator in Tosu (SAGA-HIMAT), and the Ion-beam Radiation Oncology Centre in Kanagawa (i-ROCK, under construction), are facilities specific for carbon-ion radiotherapy exclusively. One ECRIS was installed in each facility. Compact ECRISs, named Kei-series, were developed[3] to reduce the size, initial construction cost, and electric power consumption. ‘KeiGM’, and ‘KeiSA’, were manufactured with minor modifications of the magnetic configuration and the high voltage insulation. Typically, the ECRIS has to deliver C^{4+} ions at 30 kV extraction voltage with current of at least 200 eμA[4]. KeiGM and KeiSA satisfy the requirements. At GHMC were during 20130 hours of operating time three serious failures which interrupted the patient treatment and Saga-HIMAT had no failures during 7200 hours.

Recently, several countries made plans to construct such a carbon-ion radiotherapy facility. However, in order to carry out biological experiments to encourage basic research in these countries, there are occasionally requirements to produce various other ion species. Since the injector design is fixed for the acceleration of ions with a charge-to-mass ratio of about 1/3, the performance of the Kei-series does not satisfy such requirements. We developed a new compact ECRIS, named Kei3, for ion species between He^{+} and Si^{9+}[5]. Kei3 is now under commissioning. However, production of highly charged ions like Ar^{13+} or Fe^{18+} will not be possible with that source. So we tested the ion production with charge-to-mass ratio of 1/3 by an 18GHz room-temperature ECRIS, named NIRS-HEC. In order to improve the intensity, we fed RF power into an ECRIS at two frequencies, the so-called two-frequency heating technique.

TECHNICAL METHOD

18GHz NIRS-HEC ECRIS

In order to extend the range of available ion species for HIMAC, NIRS-HEC was designed to reach a high extraction voltage and a high magnetic field with normal conducting magnets. For the production of intermediate charge-state ions, optimization of the extraction configuration is most effective. The extraction electrode is electrically isolated from the ground and a high voltage power supply on the source potential safely applies the extraction voltage between the plasma electrode and the extraction electrode independent of the source potential. The position of electrode can easily be changed. With these two parameters extraction configuration can be optimised. The maximum voltage between plasma and extraction electrode is 60 kV. The maximum mirror fields at the injection and at the extraction side are 1.3 and 1.2 T, respectively. NIRS-HEC supplied various ion species since 1996[6].

For a carbon-ion radiotherapy facility, NIRS-HEC has some drawbacks. Its initial construction cost is two or three times higher than Kei-series. Electric power consumption is huge. However, due to its vertical beam extraction, the footprint including an analyzing magnet system is not so different from Kei-series shown in Figure 1. In addition, NIRS-HEC has a long lifetime even for ‘dirty conditions’ like carbon depositions. NIRS-HEC is usually operated over a half year without ~~a~~ maintenance during which the vacuum chamber is not exposed to atmosphere. All operation parameters are set by a remote control system and are able to restore by a software. The failure rate is also low. These performances are suitable for a medical facility.

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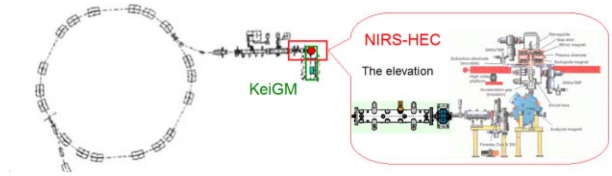

Figure 1: Footprints of NIRS-HEC and KeiGM with a carbon specified accelerator.

Two-Frequency Heating Technique

The two-frequency heating technique was initiated by ECR pioneers Jongen and Lyneis in Berkeley, and some years later more successfully by Xie and Lyneis again in Berkeley[7]. Since then many ECR laboratories have tested this technique. The two-frequency heating technique has advantages; it is effective for any kind of ion species, it is coexistent with almost other techniques, and no modification of existing structure is necessary. Between 1998 and 2013 numerous experiments were carried out in NIRS; in each experiment a positive effect of the second microwave was demonstrated[8]. The mechanism is still not completely clear. Our basic observation is that when the primary microwave power increases, the plasma shows instability and it is difficult to keep. When an additional microwave is added in the above situation, the plasma stability is improved at larger microwave power obtained by the mixture of two different frequency microwaves. The important points to obtain the highest effectiveness with this technique are as follows.

- To supply enough power for both microwaves.
- To precisely adjust the additional frequency. The best frequency depends on operation parameters; magnetic configuration, vacuum pressure, and so on.

The primary microwave source is an 18 GHz fixed frequency Klystron (KLY) amplifier system with a maximum power of 1500 W. The additional source is a travelling wave tube (TWT) amplifier system with the frequency range from 17.10 to 18.55 GHz and with maximum power of 1200 W. Of course, power stability is important for the reproducibility. Therefore, both microwave systems have installed a power feedback. The block diagram is shown in Figure 2.

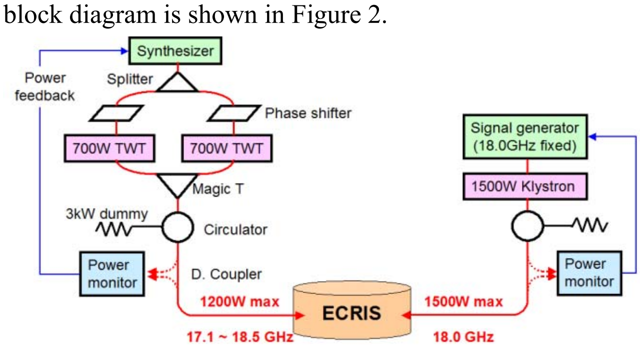

Figure 2: A block diagram of two-frequency heating system at NIRS-HEC.

MIVOC Method

Metallic ion species like Fe are especially interesting in biomedical researches, for example, to study the risks of space exploration due to galactic cosmic rays. The MIVOC is a method[9] to apply metallic vapors from volatile metallic compounds including the requested elements. MIVOC was adapted for the productions of Fe, and Ni ions. The biggest advantage of MIVOC is to be able to use a solid sample *as if it is a gas*. It is easy to operate and maintain and the equipment is small. The ion species can be changed without exposing the vacuum chamber to atmosphere. These features are also suitable for a medical facility.

The two-frequency heating technique is very sensitive to a gas pressure. For the precise and stable tuning of pressure, we used the thermal control system at a MIVOC compound container[10]. In the cases of Fe^{18+} and Ni^{19+}, the Peltier cooling system was utilized for ferrrocene and nickelocene. It works between 0 C° and room temperature.

EXPERIMENTAL RESULTS

Productions of Ar, Fe, and Ni

Figure 3 shows a typical mass spectrum of Ni from nickelocene. All operation parameters were optimised for Ni^{17+}. Peaks of oxygen appeared due to residual gas from the previous measurement. The intensity of Ni^{17+} was 26 eμA. In this case, the after-glow technique was effective[11]. The microwave powers of 18.0 GHz and 17.87 GHz were 630 W and 1100 W, respectively, while both generators were set with microwave width of 30 ms. The injection and extraction side mirror magnetic fields are 1.21 T and 0.74 T, respectively. The extraction voltage and distance between the plasma electrode and the extraction electrode are 31 kV and 20 mm, respectively. The gas flow of O_2 is 0.024 atom cc/min. The temperature of the MIVOC container is 23 C°. The vacuum pressure at the injection-side chamber was 3.3×10^{-5} Pa. Since the peak of $^{58}Ni^{18+}$ was covered by the peak of O^{5+}, the intensity was estimated at about 12 eμA from the peak of $^{60}Ni^{18+}$. Although the peak of $^{58}Ni^{19+}$ and $^{60}Ni^{19+}$ were covered, we expected an output current for $^{58}Ni^{19+}$ of a few or at least one eμA from the charge state distribution.

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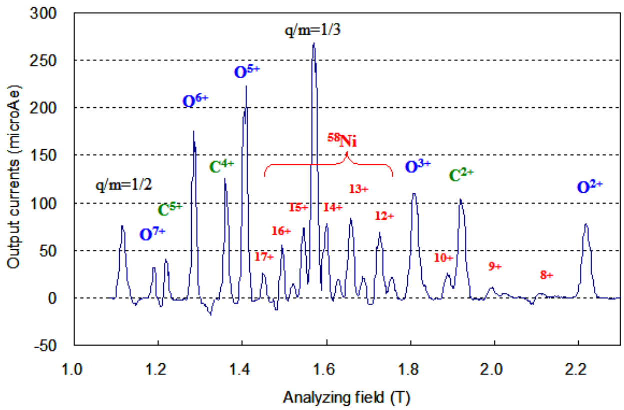

Figure 3: A typical mass spectrum of nickel ions produced with nickelocene. Oxygen gas was used as a support gas.

Production of C

Carbon production is the most important requirement for a carbon-ion radiotherapy facility. Although the two-frequency heating technique is not necessary for this purpose, we tested the effectiveness of highly-charged carbon ions. Figure 4 shows a typical mass spectrum of C from CH_4. All operation parameters were optimised for C^{5+}. The intensity of C^{5+} was 550 eμA under unsuitable conditions due to residual oxygen from previous productions. In this case, the after-glow technique was utilized. As a result, the technique was effective for C^{5+}, but not so much for C^{4+}.

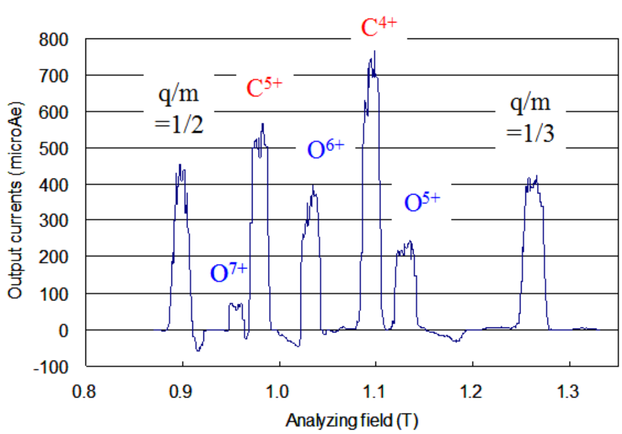

Figure 4: A typical mass spectrum of carbon ions produced with CH_4 gas. Oxygen impurities came from the previous residuals.

CONCLUSSION

Table 1 shows the highest intensity of Ar,, Fe, and Ni with the two frequency heating technique. The output currents for Fe^{18+} were 2 eμA. With this current the HIMAC facility can deliver a dose rate of several Gy/min in a diameter of 20mm at the biology experiment room shown in Figure 5, which is sufficient for cell experiments. However, it's better to obtain more intensities for animal experiments.

Table 1: Output currents of C, Ar, Fe, and Ni

Ion	5+	12+	13+	14+	15+	16+	17+	18+
C	**550**							
Ar		116	**42**	**15**				
Fe		130	120		70	41	12	**2**
Ni		110	83	78	75	56	26	12

Bold: available for acceleration by a carbon ion radiotherapy specified facility.
Ni^{19+} was estimated a few or at least one eμA from the other charge state.

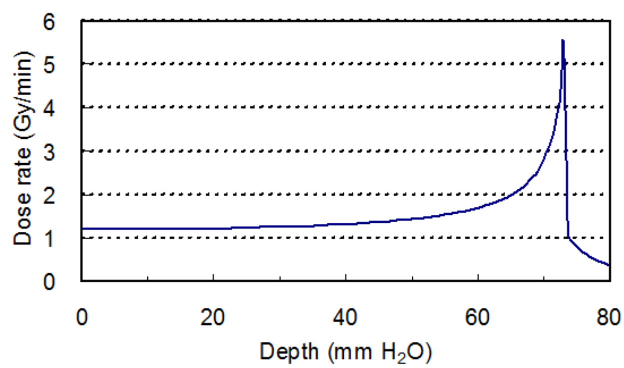

Figure 5: Estimated physical dose rate of Fe beam in a diameter of 2cm at the biology experiment room.

In order to consider the realistic possibility to use NIRS-HEC in a hospital, we must point out an important reality; an ion-source specialist is not expected in a hospital. The installation of gas bottles or MIVOC containers must be simple; complicated operation is not acceptable. All operation parameters must be stored for the software control system. How to check the reproducibility by non specialists? We must solve all of such problems.

Another problem is an interval to exchange ion species. The hysteresis appears in the routine operations to produce different ion species cyclically. It caused the delay to reproduce an expected operation condition. The reason of the hysteresis is mainly caused by the varying surface condition of the plasma chamber. So the interval time strongly depends on the ion species. It is typically a few or several hours. If the facility does not allow the interval between the treatment and the experiment, we must have two sources for exchange ion species quickly.

The importance of fine tuning of the second microwave frequency was observed in early stages of our development[12]. We guessed the additional frequency controls anisotropy of electrons' velocity distribution and it may affect the plasma instability. Some recent observations of the additional frequency dependence suggested that an electron orbit effect might play some role[8]. One approach to verify or to reject this assumption is a computer simulation. The calculation by the TrapCAD code[13] has continued by our collaborators. The result will be published soon.

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